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RESEARCH MEMORANDUM

PERFORMANCE EVALUATION OF REDUCED-CHORD ROTOR BLADING AS APPLIED TO J73 TWO-STAGE TURBINE

IV - OVER-ALL PERFORMANCE OF FIRST-STAGE TURBINE WITH REDUCED-CHORD ROTOR BLADES AT INLET CONDITIONS OF 35 INCHES OF MERCURY ABSOLUTE AND 700° R

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By Harold J. Schum

SUMMARY

The two-stage turbine from the J73 turbojet engine has previously been investigated with both standard rotor blading and reduced-chord rotor blading in order to ascertain the over-all performance characteristics of each configuration over a range of pressure ratio and speed. Because the two turbine configurations exhibited comparable performance, both having high efficiencies over wide operating ranges, it was considered of interest to determine the performance of the first stage of each unit. Necessary modifications were incorporated into the turbine, and the over-all performance characteristics of the first stage of the standard-bladed turbine were obtained. The first stage of the reduced-chord multistage turbine was then investigated similarly to that for the first-stage standard-bladed turbine and the results are included herein.

The reduced-chord first-stage turbine operated at a peak brake internal efficiency of over 91 percent at a stage over-all pressure ratio of 1.4 and at 90 percent of the design equivalent speed. The unit exhibited high efficiency over a wide range of operating variables, as found in the other J73 experimental investigations. The over-all performance of the standard and the reduced-chord first-stage turbines was comparable over the entire range investigated. Furthermore, the first stage of the multistage turbine equipped with the reduced-chord rotor blades produced approximately half the total turbine work output, as did the first stage of the standard-bladed turbine.

INTRODUCTION

The performance of the two-stage turbine from the J73 turbojet engine has been investigated at the NACA Lewis laboratory with both

[1]The information presented herein was previously given limited distribution.

standard and reduced-chord rotor blading. The experimental investigations were conducted on the turbine as a separate engine component at an inlet pressure of 35 inches of mercury absolute and at an inlet temperature of 700° R. Both turbine configurations exhibited peak efficiencies of over 90 percent and yielded wide efficient ranges of operation. The results obtained from the investigations of the standard-bladed and the reduced-chord multistage-turbine configurations are presented in references 1 and 2, respectively.

Because of the apparently good performance obtained from the multistage-turbine investigations, it was considered of interest to operate the first stages of the turbines as separate components in order to determine their performance characteristics. The multistage turbine was modified accordingly, and the first stage of the standard-bladed turbine was investigated; the results are presented in reference 3. This first stage operated at a peak efficiency of over 90 percent at a stage pressure ratio of 1.4 and 90 percent of design equivalent speed. Moreover, the single-stage turbine provided high efficiencies over a relatively wide operating range.

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The single-stage turbine configuration utilizing the reduced-chord rotor blades was then investigated over a range of speed from 20 to 130 percent of the design equivalent speed and over a range of stage pressure ratio from 1.2 to 2.8 similarly to that for the first-stage standard-bladed turbine (ref. 3). The inlet-gas state was maintained at the same conditions as for the other investigations; that is, the inlet pressure was 35 inches of mercury absolute and the inlet temperature was 700° R. The over-all performance results are again presented in terms of brake internal efficiency, equivalent work output, equivalent weight flow, equivalent rotor speed, and equivalent stage total-pressure ratio. For the convenience of the reader, the results are tabulated in table I.

SYMBOLS

The following symbols are used in this report:

E enthalpy drop based on torque measurements, Btu/lb

g gravitational constant, 32.174 ft/sec^2

N rotational speed, rpm

p static pressure, in. Hg abs

p' total pressure, in. Hg abs

p'_x static pressure plus velocity pressure corresponding to axial component of velocity, in. Hg abs

R gas constant, 53.345 ft-lb/(lb)($^{\circ}$F)

T' total temperature

w weight flow, lb/sec

$\frac{wN}{60\delta}\epsilon$ weight-flow parameter based on equivalent weight flow and equivalent rotor speed

γ ratio of specific heats

δ ratio of inlet-air pressure to NACA standard sea-level pressure, $p'_1/29.92$ in. Hg abs

ϵ function of γ, $\frac{\gamma_0}{\gamma_e}\left[\frac{\left(\frac{\gamma_e + 1}{2}\right)^{\frac{\gamma_e}{\gamma_e - 1}}}{\left(\frac{\gamma_0 + 1}{2}\right)^{\frac{\gamma_0}{\gamma_0 - 1}}}\right]$

η_i brake internal efficiency, defined as the ratio of actual turbine work based on torque measurements to ideal turbine work based on inlet total pressure p'_1 and discharge total pressure corrected for whirl $p'_{x,2}$

θ_{cr} squared ratio of critical velocity to critical velocity at NACA standard sea-level temperature of 518.4° R, $\frac{\frac{2\gamma}{\gamma + 1} gRT'}{\frac{2\gamma_0}{\gamma_0 + 1} gRT'_0}$

τ torque, ft-lb

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CW-1 back

Subscripts:

cr critical

e engine operating conditions

h hub

t tip

x axial

0 standard sea-level conditions

1 turbine-inlet measuring station

2 turbine-outlet measuring station

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APPARATUS AND INSTRUMENTATION

Apparatus

The standard and the reduced-chord rotors of the multistage turbine are described in detail in references 1 and 2, respectively. The modifications required to operate the turbine as a single-stage unit are described in reference 3 and were incorporated herein in order to determine experimentally the performance of the single-stage turbine utilizing reduced-chord rotor blades. The ducting required for the turbine air supply and exhaust was unchanged. The power developed from the turbine was again absorbed by the two dynamometers. A photograph of the setup, showing the various components used to investigate the first stage of the reduced-chord turbine configuration, is presented in figure 1.

Turbine Instrumentation

The single-stage turbine was instrumented in the same manner as that described in the corresponding investigation of the standard-bladed turbine (ref. 3). Measurements of total pressure, static pressure, and temperature were made at the turbine inlet and outlet (stations 1 and 2, respectively, fig. 2). The pressures and temperatures were measured as described in reference 3, as were turbine rotor speed, torque output, and air weight flow. The instrumentation at the discharge measuring station duplicated the interstage instrumentation present but not reported in the multistage-turbine investigations of references 1 and 2.

PROCEDURE

Turbine-inlet total pressure p_1' was calculated by the method described in reference 1. The turbine-outlet total pressure $p'_{x,2}$, defined as the static pressure plus the velocity pressure corresponding to the axial component of the absolute velocity, was computed. This calculated discharge total pressure penalizes the first-stage turbine for the kinetic energy of the rotor-exit tangential velocity component; the first-stage efficiencies are, therefore, on the conservative side.

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The single-stage turbine, equipped with the reduced-chord rotor blades, was operated over a range of speed from 20 to 130 percent of the design equivalent speed (4041 rpm) and over a range of equivalent stage total-pressure ratio $p_1'/p'_{x,2}$ from 1.2 to 2.8 with constant nominal inlet values of pressure and temperature of 35 inches of mercury absolute and 700° R, respectively.

RESULTS AND DISCUSSION

The variation of equivalent shaft work output $E/\theta_{cr,1}$ with the weight-flow parameter $\frac{wN}{60\delta}\epsilon$ is shown in figure 3 for lines of constant turbine rotor speed $N/\sqrt{\theta_{cr,1}}$ and constant equivalent total-pressure ratio $p_1'/p'_{x,2}$. Brake internal-efficiency contours are also included. (All performance parameters presented have been corrected to NACA standard sea-level conditions of 29.92 in. Hg abs and 518.4° R.) It can be readily noted on the performance map (fig. 3) that efficiencies of 91 percent were obtained in the vicinity of an over-all stage pressure ratio of 1.4 and 90 percent of the design equivalent speed. Furthermore, the performance map indicates that high efficiencies were obtained over a relatively wide range of speed and pressure ratio. The stage performance and the region of peak efficiency are similar to those reported in reference 3 for the single-stage turbine equipped with standard rotor blades. It is interesting to note that use of reduced-chord rotor blading in a multistage turbine results in a slight decrease in peak efficiency as compared with the results obtained with the standard rotor blading (ref. 2), whereas the inverse was found for the single-stage turbine configuration. The differences are small, however, and no definite conclusions can be realistically drawn from them.

The performance map (fig. 3) was calculated from faired values of equivalent weight flow $\frac{w\sqrt{\theta_{cr,1}}}{\delta_1}\epsilon$ and equivalent torque-output $\frac{\tau}{\delta_1}\epsilon$; these data are presented in figures 4 and 5, respectively. As indicated on figure 4, it appears that the turbine stator chokes at over-all stage pressure ratios greater than 2.3 and at an equivalent weight flow of 42.65 pounds per second. These values agree with the corresponding values obtained in the investigation of the first-stage turbine having standard rotor blades (ref. 3). Comparison of the weight-flow curves for the two single-stage turbine configurations indicates that there is no appreciable variation.

Comparison of the faired values of equivalent torque output (fig. 5) with those obtained with the first-stage standard-bladed turbine (ref. 3) indicates relatively close agreement for the two first-stage 3210
turbine configurations. A maximum variation of only 2 percent prevailed at the higher values of pressure ratio and speed, the standard-bladed turbine producing more torque.

The simultaneous small variation of equivalent weight flow and torque output with pressure ratio is reflected in the computed brake internal efficiencies. From a comparison of the efficiency contours as obtained from the two first-stage turbine configurations, it can be seen that, at speeds of 60 percent and above and over the range of stage pressure ratio investigated, the two turbine configurations exhibited the same efficiencies within 2 percent except for low pressure ratios at 120 percent of design speed, where the reduced-chord turbine was 3 percent less efficient than the standard-bladed turbine. It can be concluded, however, that the over-all performance of the standard and the reduced-chord first-stage turbines was generally comparable over the entire range investigated.

It is deemed important to point out that the first-stage turbine does not operate over the entire range of stage pressure ratio presented when incorporated in the multistage unit. As stated in reference 1, design shaft work for the J73 multistage turbine was 28.48 Btu per pound. From the investigation of the multistage turbine equipped with the reduced-chord rotor blading (ref. 2), a measured first-stage pressure ratio of 1.60 was observed at the multistage design operating point. This measured stage pressure ratio corresponds to a calculated stage pressure ratio of approximately 1.62. If the latter is considered the design first-stage pressure ratio, it can be noted on the performance map that an equivalent shaft work output of approximately 14.40 Btu per pound was produced. This represents approximately half the total turbine design work output. The same result was obtained with the first-stage turbine with standard rotor blades (ref. 3). Hence, it can be concluded that each stage of the multistage J73 turbine, whether equipped with standard rotor blading or with reduced-chord rotor blading, produces approximately the same work output.

SUMMARY OF RESULTS

An investigation of the over-all performance of the first stage of the reduced-chord multistage J73 turbine produced the following results:

1. A peak efficiency of over 91 percent was obtained at an over-all stage pressure ratio of 1.4 and 90 percent of the design equivalent speed.

2. The turbine exhibited high efficiency over a wide range of equivalent speed and over-all stage pressure ratio.

3. The over-all performance of the standard and the reduced-chord first-stage turbines was comparable over the entire range investigated.

4. At the design operating point of the correspondingly bladed multistage turbine, the first stage produced approximately half the total turbine work output.

REFERENCES

1. Berkey, William E., Rebeske, John J., Jr., and Forrette, Robert E.: Performance Evaluation of Reduced-Chord Rotor Blading as Applied to J73 Two-Stage Turbine. I - Over-All Performance with Standard Rotor Blading at Inlet Conditions of 35 Inches of Mercury Absolute and 700° R. NACA RM E52G31, 1957.

2. Schum, Harold J., Rebeske, John J., Jr., and Forrette, Robert E.: Performance Evaluation of Reduced-Chord Rotor Blading as Applied to J73 Two-Stage Turbine. II - Over-All Performance at Inlet Conditions of 35 Inches of Mercury Absolute and 700° R. NACA RM E53B25, 1957.

3. Schum, Harold J.: Performance Evaluation of Reduced-Chord Rotor Blading as Applied to J73 Two-Stage Turbine. III - Over-all Performance of First-Stage Turbine with Standard Rotor Blades at Inlet Conditions of 35 Inches of Mercury Absolute and 700° R. NACA RM E53L28a, 1957.

TABLE I. - DATA SUMMARY FROM EXPERIMENTAL INVESTIGATION OF J73 MODIFIED FIRST-STAGE TURBINE WITH REDUCED-CHORD ROTOR BLADING

Calculated over-all total-pressure ratio, $p_1'/p_{x,2}'$	Over-all total-pressure ratio, p_1'/p_2'	Over-all total-to-static pressure ratio at hub, $p_1'/p_{h,2}$	Over-all total-to-static pressure ratio at tip, $p_1'/p_{t,2}$	Inlet total pressure, p_1', in. Hg abs	Inlet total temperature, T_1', °R	Outlet total temperature, T_2', °R	Engine speed, N, rpm	Weight flow, w, lb/sec	Torque, τ, ft-lb
1.158	1.116	0.837	0.845	34.88	700.0	685.8	941	33.46	991
1.161	1.148	.839	.842	34.84	700.0	677.1	1885	32.89	745
1.162	1.158	.843	.841	34.87	699.9	674.8	2828	31.17	519
1.163	1.164	.841	.841	35.03	699.9	674.7	3306	30.88	438
1.267	1.170	.748	.767	34.78	701.4	608.1	944	38.70	1438
1.239	1.209	.778	.778	34.80	700.3	669.8	1884	37.34	1089
1.241	1.239	.782	.776	34.81	700.3	664.1	2824	36.17	850
1.236	1.232	.786	.782	34.81	700.1	664.1	3303	35.12	713
1.227	1.225	.791	.791	34.98	701.1	664.0	3780	34.27	576
1.226	1.222	.792	.794	35.12	700.0	667.0	4254	33.99	495
1.418	1.244	.650	.678	34.77	700.5	674.4	936	41.47	1923
1.424	1.331	.657	.666	34.81	700.5	658.3	1886	41.42	1656
1.402	1.371	.678	.671	34.73	700.5	649.2	2825	40.74	1346
1.406	1.391	.676	.670	34.80	700.5	644.9	3304	40.61	1251
1.398	1.395	.683	.674	34.79	700.5	643.6	3773	39.89	1089
1.398	1.389	.682	.678	34.87	700.4	645.7	4244	39.37	948
1.395	1.396	.682	.681	34.78	700.4	643.5	4717	39.02	847
1.405	1.402	.676	.678	34.86	700.3	643.5	5191	38.92	759
1.644	1.339	.537	.581	34.74	701.6	666.8	944	42.43	2339
1.564	1.397	.584	.602	34.81	701.6	651.3	1883	42.34	1959
1.536	1.464	.607	.605	34.78	701.5	639.1	2830	42.10	1663
1.512	1.476	.621	.615	34.71	701.5	636.5	3306	41.70	1490
1.527	1.502	.617	.611	34.75	700.5	632.2	3774	40.37	1487
1.513	1.502	.623	.615	34.73	700.5	631.0	4248	41.08	1230
1.515	1.500	.620	.618	34.78	700.5	632.1	4719	40.85	1103
1.500	1.490	.625	.628	34.76	701.5	633.0	5196	40.31	948
1.501	1.495	.625	.628	34.77	700.5	633.9	5665	40.21	850
1.510	1.498	.619	.626	34.84	700.5	635.0	6135	40.17	748
1.938	1.481	.436	.487	34.72	700.6	658.8	943	42.62	2651
1.796	1.502	.493	.515	34.72	700.6	643.7	1885	42.58	2307
1.725	1.593	.526	.532	34.84	700.6	628.0	2830	42.53	1937
1.712	1.616	.535	.531	34.72	700.6	622.5	3290	42.48	1804
1.694	1.644	.544	.534	34.71	700.7	619.0	3773	42.38	1652
1.694	1.666	.546	.535	34.77	700.7	615.7	4250	42.34	1529
1.697	1.669	.545	.536	34.71	700.5	613.7	4718	42.06	1399
1.696	1.672	.557	.538	34.72	700.5	613.6	5192	42.01	1283
1.669	1.670	.556	.549	34.76	700.5	616.2	5666	41.63	1125
1.672	1.667	.551	.552	34.79	700.5	615.3	6140	41.54	1001
2.244	1.604	.351	.400	34.69	699.6	659.5	938	42.65	2901
2.150	1.639	.388	.415	34.73	700.6	634.8	1886	42.65	2574
2.019	1.750	.429	.440	34.70	700.7	615.4	2825	42.60	2268
1.964	1.776	.450	.450	34.74	700.7	608.7	3305	42.61	2085
1.906	1.788	.471	.463	34.75	700.6	605.0	3775	42.58	1902
1.916	1.842	.470	.459	34.76	700.6	600.6	4244	42.51	1804
1.896	1.864	.478	.462	34.77	700.6	598.1	4721	42.56	1656
1.890	1.860	.480	.466	34.80	700.6	596.0	5190	42.52	1536
1.867	1.857	.487	.474	34.73	700.6	598.8	5663	42.31	1382
1.873	1.870	.483	.475	34.79	700.6	598.7	6140	42.31	1269
2.510	1.681	.282	.340	34.72	700.7	658.9	935	42.70	2991
2.477	1.738	.311	.341	34.65	700.7	631.4	1889	42.53	2756
2.321	1.873	.351	.364	34.70	700.7	610.6	2830	42.65	2457
2.224	1.902	.377	.388	34.71	700.7	601.8	3302	42.61	2292
2.157	1.932	.400	.398	34.81	700.7	593.1	3775	42.63	2109
2.132	1.979	.409	.400	34.69	701.7	588.6	4250	42.61	1982
2.075	1.997	.426	.411	34.72	700.7	585.9	4717	42.54	1845
2.114	2.055	.417	.400	34.75	700.6	583.8	5186	42.53	1725
2.077	2.027	.427	.412	34.74	700.6	581.6	5665	42.48	1574
2.101	2.076	.421	.406	34.77	700.6	581.4	6139	42.45	1461
2.675	1.845	.265	.293	34.67	701.6	630.7	1882	42.61	2812
2.579	1.953	.292	.314	34.71	700.6	609.2	2829	42.61	2552
2.508	2.025	.312	.326	34.73	700.6	595.7	3304	42.61	2425
2.454	2.074	.346	.335	34.67	701.7	584.2	3773	42.59	2270
2.405	2.149	.342	.343	34.68	701.6	577.6	4244	42.55	2147
2.332	2.173	.361	.353	34.73	701.6	576.0	4715	42.55	1989
2.357	2.241	.347	.354	34.76	701.6	572.7	5191	42.57	1884
2.334	2.274	.354	.349	34.75	700.6	569.3	5665	42.57	1743
2.293	2.255	.273	.358	34.72	700.6	569.1	6125	42.57	1602
2.732	2.218	.253	.283	34.67	700.6	580.8	3758	42.64	2330
2.734	2.227	.266	.282	34.70	701.1	580.8	3770	42.64	2327
2.705	2.321	.276	.282	34.70	700.7	574.6	4246	42.60	2222
2.649	2.368	.292	.291	34.78	701.7	570.2	4717	42.60	2081
2.597	2.412	.306	.297	34.78	701.7	565.7	5190	42.54	1951
2.558	2.438	.314	.303	34.71	700.6	564.4	5668	42.58	1820
2.586	2.499	.309	.297	34.81	700.6	562.2	6144	42.58	1697
2.777	2.433	.261	.272	34.69	701.5	569.8	4724	42.50	2102
2.833	2.526	.246	.253	34.65	701.7	564.6	5198	42.50	1986
2.904	2.592	.241	.238	34.73	701.7	562.8	5685	42.50	1873
2.968	2.644	.214	.202	34.72	701.6	561.9	6141	42.50	1750

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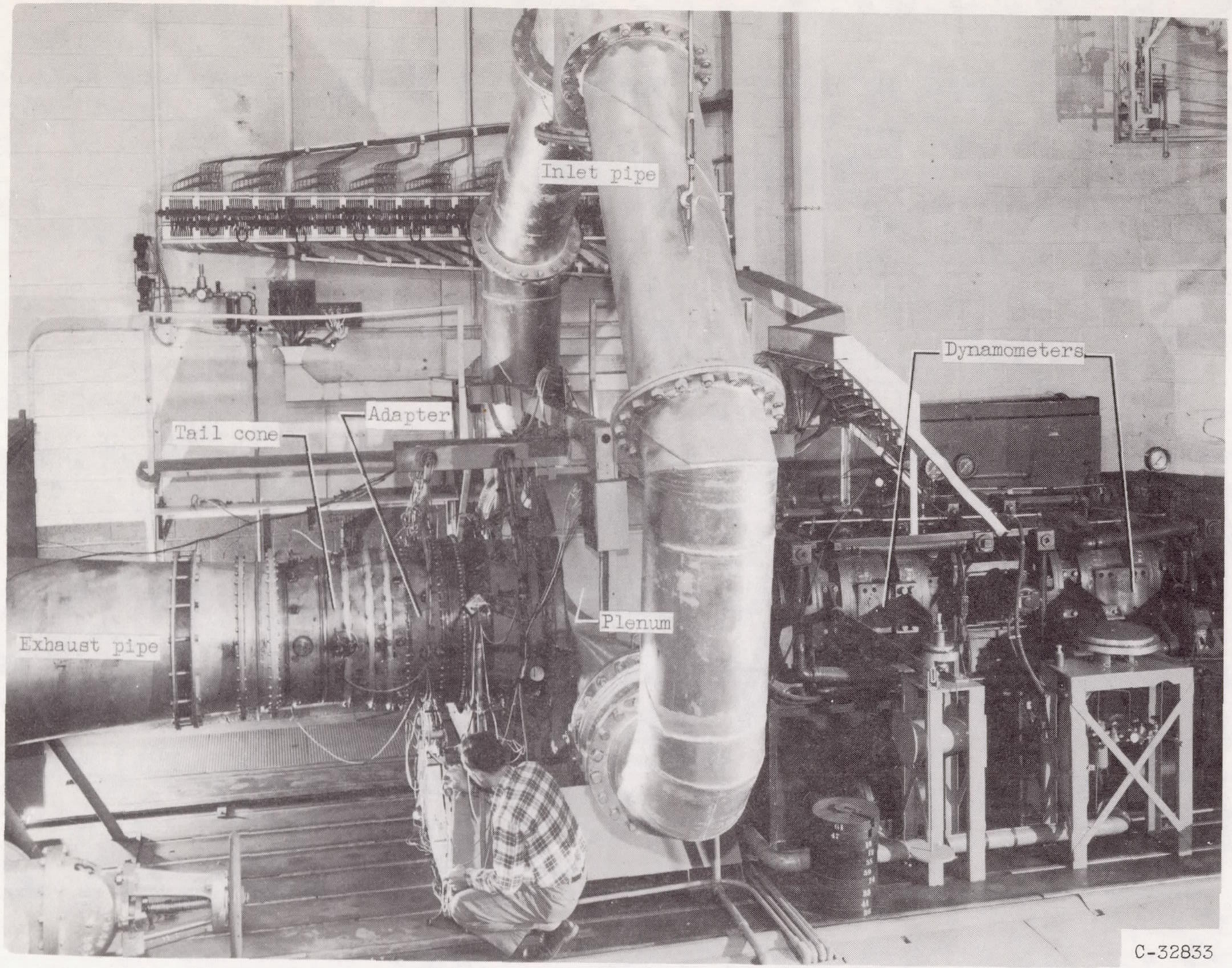

Figure 1. - Setup for investigation of performance of J73 single-stage turbine equipped with reduced-chord rotor blading.

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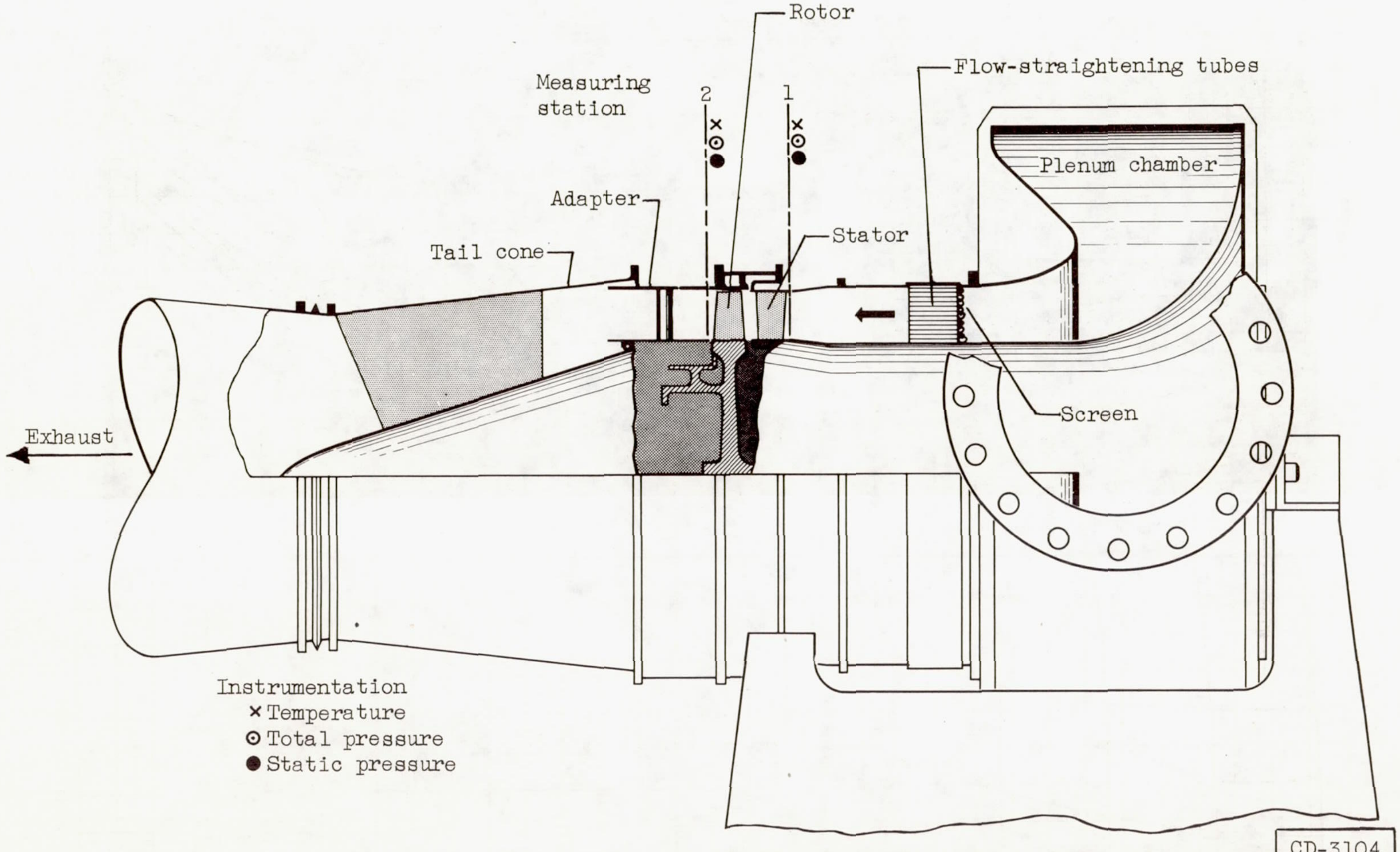

Figure 2. - Schematic diagram of single-stage-turbine assembly and instrumentation.

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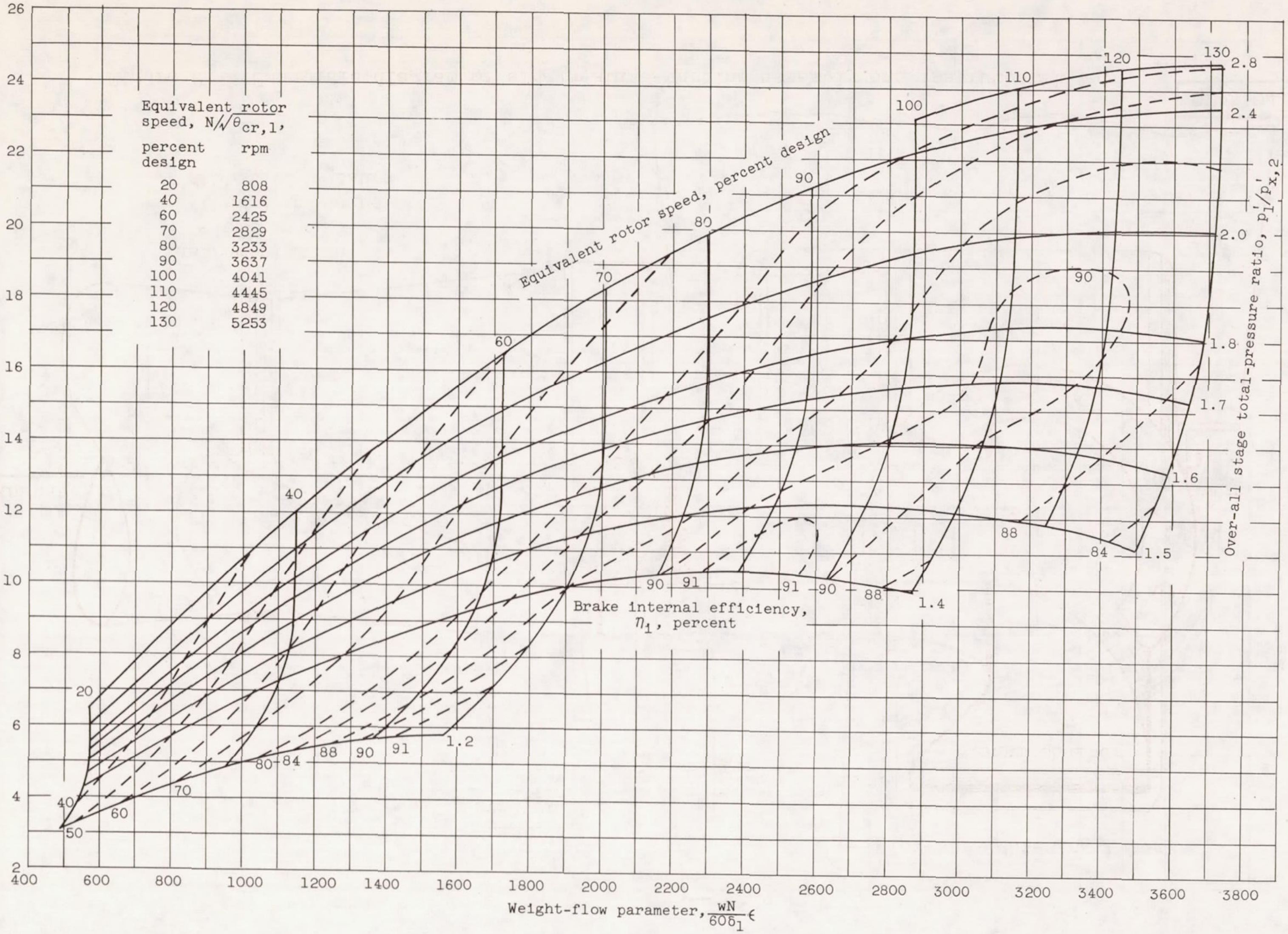

Figure 3. - Over-all performance of J73 modified single-stage turbine equipped with reduced-chord rotor blading. Turbine-inlet pressure, 35 inches of mercury absolute; turbine-inlet temperature, 700° R.

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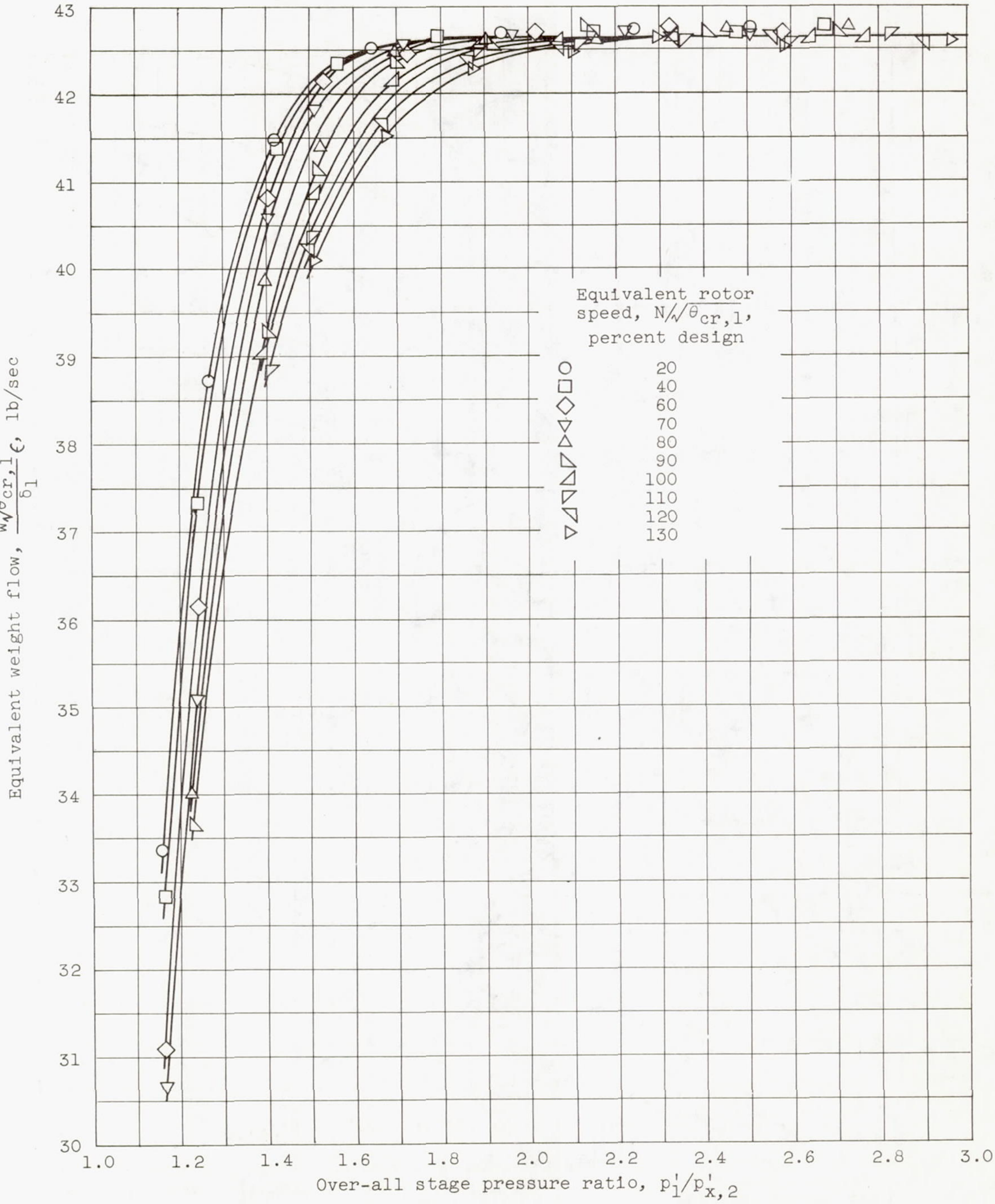

Figure 4. - Variation of equivalent weight flow with over-all stage pressure ratio at different speeds for J73 modified single-stage turbine equipped with reduced-chord rotor blading.

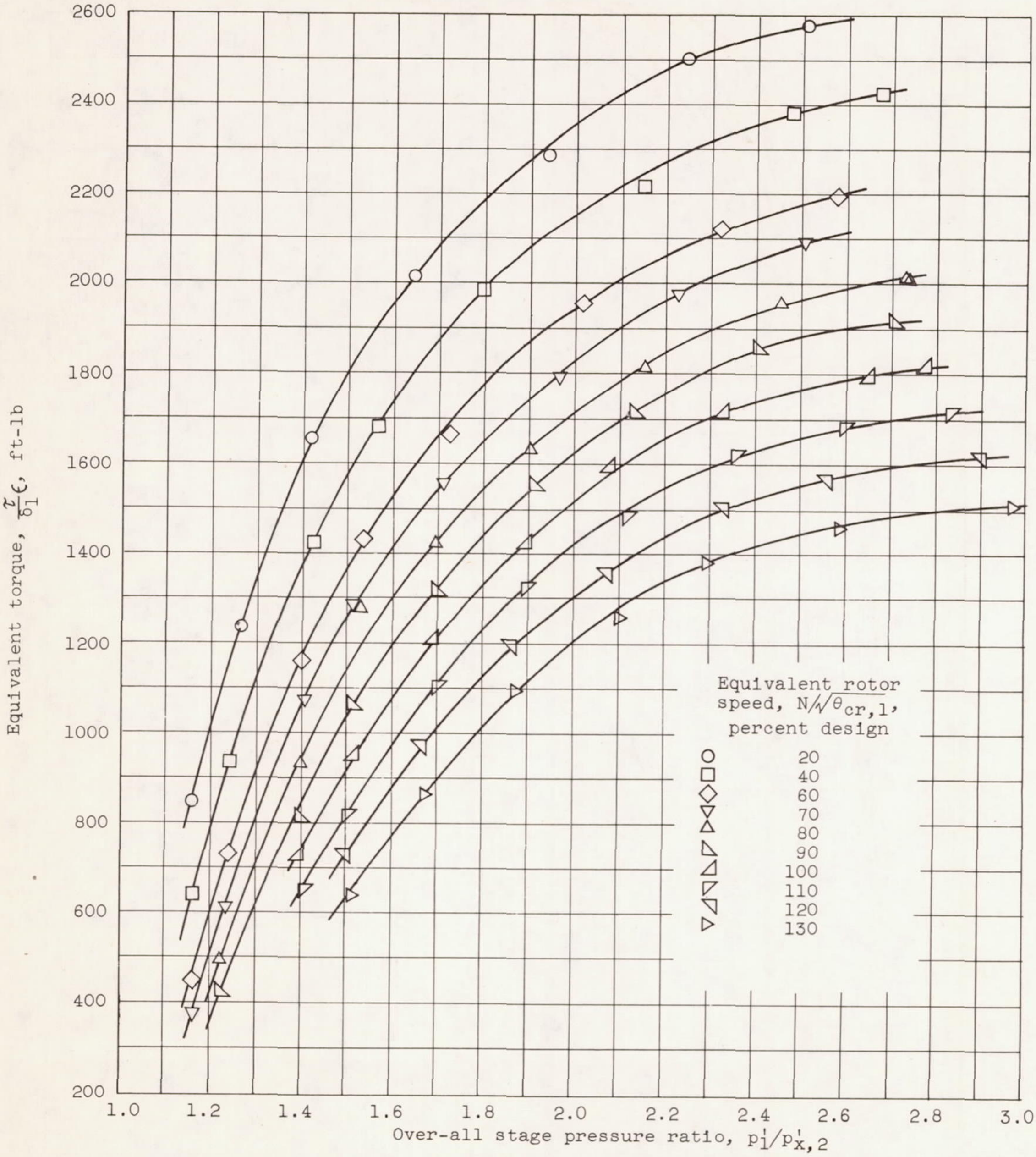

Figure 5. - Variation of equivalent torque with over-all stage pressure ratio at different speeds for J73 modified single-stage turbine equipped with reduced-chord rotor blading.

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